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THE STRUCTURE OF CHONDRULES AND CHONDRITES

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Investigations on the structure of chondrules in chondritic meteorites, on the basis of granolumetric, gravitational, and magnetic analyses of detrital rocks and slimes for defining the nature of the interstitial silicate, nickeliron, and troilite, are discussed. Tabulated and plotted data on various chondrites fallen in Russia indicate that the chondrules were formed from drops of liquid (melting of finely divided solids, condensation of gases), that formation of the impurities (sulfides, etc.) took place after solidification of the chondrules, and that the interstitial silicates were formed from the detritus of the glass constituents of the chondrules.

The formation of chondrules is one of the fundamental questions in the problem of the origin of meteorites. However, the information on the structure of the chondrules themselves and on the silicate particles of the cementing matrix of the chondrules is insufficient and is confined mainly to the results of microscopic examinations of sections, usually of transparent sections.

To define a number of the missing characteristics relating to the structure of the chondrules and to elucidate the nature of the silicate particles which, together with nickel-iron and troilite, fill the spaces between the chondrules and their fragments, we used methods of analysis of detrital rocks and slimes

^{*} Numbers in the margin indicate pagination in the original foreign text.

(granulometric analysis, gravitational separation, magnetic and electromagnetic separation, studies under the binocular magnifier, immersion method) parallel with a conventional study on transparent and polished sections*.

1. Experimental Materials

Despite the fact that most meteorites are chondrites, a relatively small proportion of them are not altered by recrystallization and can be used, as various investigators have emphasized (Bibl.1, 2, and others), in studying the primary features of their structure, as a criterion for the conditions of formation of chondrules and chondrites.

Further than that, not all of the chondrites not altered by recrystallization are suitable for study by the method selected. Only spherical chondrites are useful here. In these chondrites, the chondrules may be easily detached from the matrix without breaking them. The chondrites of Bjurböle, Saratov, Nikol'skoye and others belong to this type.

In other varieties of chondrites not altered by recrystallization, i.e., which still have the glass mass in the chondrules [for example, the type of the Manych chondrite (Bibl.3) and others], the chondrules cannot be directly separated without destroying them; here they split together with the cementing matrix. The same applies to the carbonaceous chondrites, which are also not altered by recrystallization; the separation of the chondrules is difficult here, because of the generally fine grain of these meteorites and of their

^{*} We take this opportunity to express our thanks to N.N.Batyreva (Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, USSR Academy of Sciences) for her fractional separation of a specimen of the Saratov chondrite, a task performed with great skill.

chondrules, to say nothing of the limited quantity of material of this type.

The Saratov chondrite offers a highly useful material for this problem, and we have performed a more or less systematic study on this type, using the

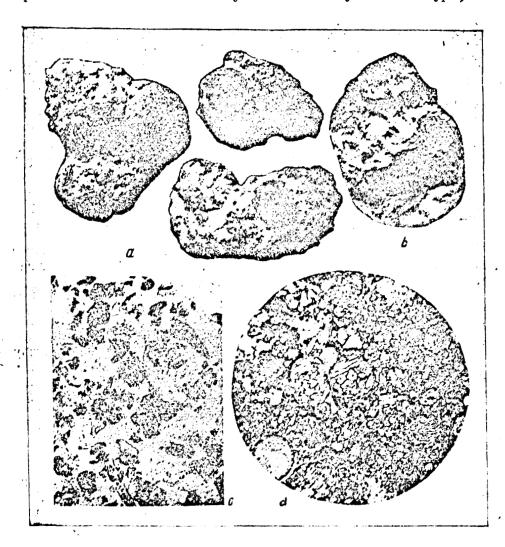


Fig.1 The Saratov Chondrite

a - Lumps from the +2 mm fraction, consisting of small chondrules and mass of silicate fragments, with cementing particles of nickel-iron and grains of troilite; b - Natural fragment of a chondrule, whose cleavage plane is in direct contact with the chondrule cementing mass; c - Particles of silicates from the chondrule matrix, fragments of minerals, and chondrules which show (bottom left) the eccentric-radiate arrangement of the tiny prisms and traces of the skeletal structure of individual minerals; fraction -0.1/4 mm, immersion preparation, fluid with N = 1.690; polarized transmitted light, without analyzer; d - General microstructure pattern; chondrules of varying structure lying close together; transmitted polarized light, without analyzer, diameter of field of view: d = 5.6 mm.

methods selected. This meteorite is a typical spherical chondrite, with a large amount of material, repeatedly investigated by various methods.

We also investigated the chondrules of the Nikol'skoye meteorite which has recently been studied partly by the same methods (Bibl.4), and chondrules of the spherical Yelenovka chondrite (Bibl.5) which is still spherical but already shows a recrystallized matrix and partly recrystallized chondrules, with a coarse-grained excellently preserved texture.

A comparison with other not yet recrystallized chondrites and chondrules was performed, mainly on transparent and polished slides, as well as by macroscopic means.

The Saratov meteor fell on October 6, 1918 (Bibl.6). It consisted of several masses which spread over a distance of 130 - 140 km (Bibl.7 - 9).

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The total weight of the meteoritic matter collected was about 221 kg.

The meteorite is characterized by an ash-gray color. It is neutral-gray in spectrophotometric properties (Bibl.10). The structure is distinctly coarse-grained, abundant in varied chondrules (Bibl.9, 11 - 13, and others) forming over 80 vol.% of the meteorite (Fig.1, a and d). The meteorite is brittle and readily crumbles. Its total porosity is estimated at 18 vol.% (Bibl.14). Chemically, the Saratov meteorite is close to the average composition of the chondrites (cf. Table 4). A chlorine content of 0.011% has been found (Bibl.15). The viscosity of the meteoritic matter at its melting point (near 1400°C) has been determined as 1.2 × 10⁴ poises (Bibl.16). From the Ar⁴⁰/K⁴⁰ ratio, the age of its meteoritic matter has been determined as 3.7 × 10⁹ years and that of its chondrules, as 3.2 × 10⁹ years (Bibl.17). Its cosmic age according to Ne²¹/Na²² is estimated as 21.5 × 10⁶ years and according to He³/H³, as 18.4 × × 10⁶ years (Bibl.18).

2. Fractionation of the Saratov Chondrite and its Granulometric Composition

To fractionate the Saratov chondrite and investigate its fractions, a lump weighing 57.1 gm was broken off a fresh specimen (specimen No.319 of the collection of the Committee on Meteorites, USSR Academy of Sciences) without iron oxide spots and without a fused crust, belonging to the mass that fell near the Village of Belaya Gora.

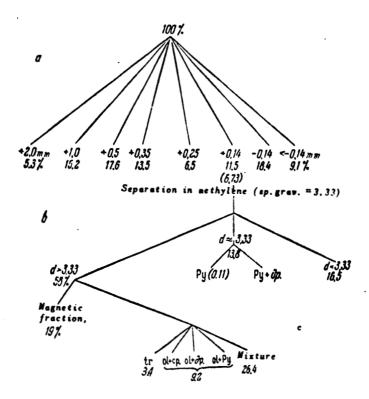


Fig.2 Diagram of Fractionation of Saratov
Chondrite Specimen (cf. Table 1)

a - Screen fractionation and granulometric composition.

b - Separation of the +0.14 mm fraction in heavy liquid followed by magnetic and electromagnetic separation into electromagnetic fractions.

It was perceptible to the naked eye that the meteorite was very rich in chondrules and that it was coarse and readily disintegrated. The specimen was friable and easily crumbled by hand, as far as this could be done without dis-

turbing the original shape of component parts. The individual denser pieces or lumps were ground in an agate mortar under light pressure.

In the grinding, some of the larger chondrules and denser lumps of chondrules and their cementing mass (Fig.1, a) were easily separated and were individually screened into fractions of 0.25, 0.14, and 0.5 mm. The rest of the 18

TABLE 1

GRANULOMETRIC COMPOSITION OF SARATOV CHONDRITES AND CHARACTERISTICS OF PARTICLES OF THE FRACTIONS

Frac- tion No.	Size of Fraction Fraction (): cles, weight in gm		Characteristic of Particles of Fraction	cles	ity of Poin Fracts of Total Fragments of Chondrules	ion, Veight	Remarks	
1	+2.0	5.3 (3.20)	Chondrules Fragments of chondrules Lumps of smaller chondrules and cementing matter		14	14 70		
2	+1.0	15.1 (8.40)	Chondrules Fragments of chondrules Lumps (cf. fraction 1)	39	21	40	Fig. 1,b	
3	+0.5	17.6 (9.95)	Chondrules Fragments of chondrules Lumps	72	5	23		
4	+0.35	13.5 (7.69)	Chondrules Fragments of chondrules Lumps	10-20	90-80	none		
5	+0.25	6.5 (3.72)	Chondrules Fragments of chondrules Lumps	3-4	96—97	none		
6	+0.14	11.7 (6.73)	Chondrules Fragments of chondrules from intergrowth of minerals and glass Fragments of minerals		Ground- mass		Fig. 1, d	
7	-0.14	18.3 (10.5)	Chondrules Fragments of chondrules from intergrowth of minerals and glass Fragments of minerals		Ground- mess			
8	<-0.1	3,0 (4.61)	Fragments of minerals, glass, and chondrules					

^{*} Rough estimate

disintegrated specimen was separated into the fractions +0.35, + 0.25, + 0. 11_{+} , -0. 11_{+} mm. The fractions beginning with +0.35 mm and smaller were cautiously

triturated with the index finger in a porcelain dish and washed with acetone to separate the chondrules from the cementing mass. The washing was likewise performed under light grinding of the powder. The finer material separated by this operation was combined with the fractions of the corresponding size.

By screening, we obtained eight fractions with particles larger than 2 mm and smaller than 0.14 mm (< -0.14 mm) (see diagram in Fig.2). The loss of material during the screening was about 4 wt.% (2.3 gm). The obtained granulometric composition of the Saratov chondrite is given in Table 1 (cf. also Fig.2).

The fractions were examined under a binocular magnifier (binocular stereo-scopic microscope, model MBS-1), with occasional check tests on the individual particles in immersion preparations. The results are also given in Table 1.

The fraction +0.1/4, from a preliminary examination under the binocular microscope and in immersion preparations, is rich in particles of the cementing mass; to separate the monomineral fractions it was fractionated in iodo— /39 methylene of sp. gr. 3.33. The fractions were washed with acetone. We obtained three fractions with specific gravities of > 3.33; ≈ 3.33; and < 3.33. From the fraction with a specific gravity above 3.33, we separated a magnetic fraction. The nonmagnetic remainder of this fraction was fractionated on an electromagnet (cf. diagram in Fig.2, b). The electromagnetic fractions were not monomineral; they are arbitrarily called monomineral in accordance with the predominantly present mineral.

An attempt to separate the fraction with particles of -0.14 mm did not give the desired results.

The specimens of all stages of separation were viewed under the binocular lens. The finer powders were also viewed in immersion preparation under the

polarizing microscope. Particles of the fractions were then studied directly under the binocular lens and, depending on their size, in immersion preparations under the polarizing microscope. In some cases transparent and polished slides were prepared from the particles of the chondrules, the fractions of the chondrules, the minerals and the lumps.

I. CHONDRULES

A. Morphology of Chondrules

The morphological properties of chondrules (i.e., size, shape, surface texture, and cleavage of chondrules) together with their other properties (such as color of the chondrules, general make-up, and texture of the aggregate composing the chondrules) were determined mainly under the binocular microscope at magnifications of × 6 to 56. The mineralogical composition of the chondrules and their internal structure were constantly checked by examining under the microscope immersion preparations of the chondrules or of their parts, or transparent and polished sections specially prepared in individual cases.

1. Size and size distribution of the chondrules. The chondrules were observed in seven fractions (cf. Table 1); their size varied from less than 0.14 to more than 2 mm. The results of a measurement by size and a count by size for one chondrule are given in the form of a histogram (Fig.3). In counting chondrules of nonspherical form, we allowed for the greatest diameter of the chondrule. The histogram shows that chondrules approximately 0.7 to 1.5 mm in size predominate in the Saratov chondrite. It is well possible that chondrules of a diameter below 0.14 mm are just as numerous, but they were not counted since some of them had not been separated from the larger lumps. The distribution shown is approximate, since some of the chondrules which remained enclosed

in the lumps were not taken into account.

Per one square centimeter of the Saratov meteorite there are 69 chondrules of the size of the first six fractions, i.e., from more than 2 mm to more than 0.14 mm. Their quantitative distribution is shown in Fig.4. This number is almost the same as the corresponding value found by P.N.Chirvinskiy in a count of the chondrules of the Saratov meteorite in transparent sections (Bibl.9): 66 chondrules/cm².

Figure 3 also gives a size distribution of the chondrules in the Nikol'skoye chondrite. In this chondrite, the greater number of chondrules were 0.8 to

1.9 mm in size (cf. Bibl.4).

2. Shape of the chondrules. The common shapes of the chondrules are not completely covered by the conventional forms: spherical, ellipsoidal, droplike, irregular, and polyhedral. Other shapes frequently encountered include cylindrical, elongated drop, pyriform, lenticular, and all possible variations of ellipsoidal shape (Fig.5, a, Fig./4, etc.). All these forms, as well as the //40 "fins" of the polyhedral chondrules, are rounded. Characteristic for the chondrules are the tail-like spurs which are sometimes easy to mistake for growths adhering to the chondrules, smaller chondrules, or particles of the cement (cf. Fig.5, a, lower right sides), etc.

The same shapes of chondrules are common to the chondrules of the Nikol'-skoye, Yelenovka, and other meteorites.

Different shapes are encountered in chondrules of different size. The most varied shapes are observed in the fractions over 0.14 mm; in all probability, elongated shapes predominate. The spherical shape of chondrules predominates in the fractions of +0.14 mm and smaller.

Modifications of chondrule shape. Modifications of the common shapes of

chondrules occur. These consist either in the appearance of convexities or growths on the chondrules, or in an increase in the volume of the chondrule, accompanied by a loss of its regular shape, or else in the appearance of pits and concavities on the chondrules (Fig.5).

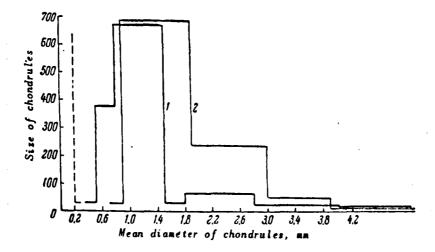


Fig.3 Histogram of Approximate Size Distribution of Chondrules in the Spherical Chondrites of Saratov and Nikol'skoye 1 - Saratov chondrite, total number of chondrules: 1300; 2 - Nikol'skoye chondrite, total number of chondrules: 1020.

Depending on the number, size, and shape of such growths, a chondrule may acquire an irregular and complex shape and sometimes increase in volume, resembling a "swelling" (some of the chondrules in Fig.6, a, b). In the case of pits, formed by the indentation of one chondrule by another (which makes it possible to call them depressions), a dent appears on the chondrule, usually in the form of regular holes of varying size. In the sections (cross sections along the hole radii), the chondrules have a lunar shape.

The character of the changes in the originally simple shapes of the chondrules is various, but all variations are obviously connected with either the conglomeration or the association of two or more chondrules. This long established fact [cf., for example (Bibl.19 - 21, 13) and many others] must be

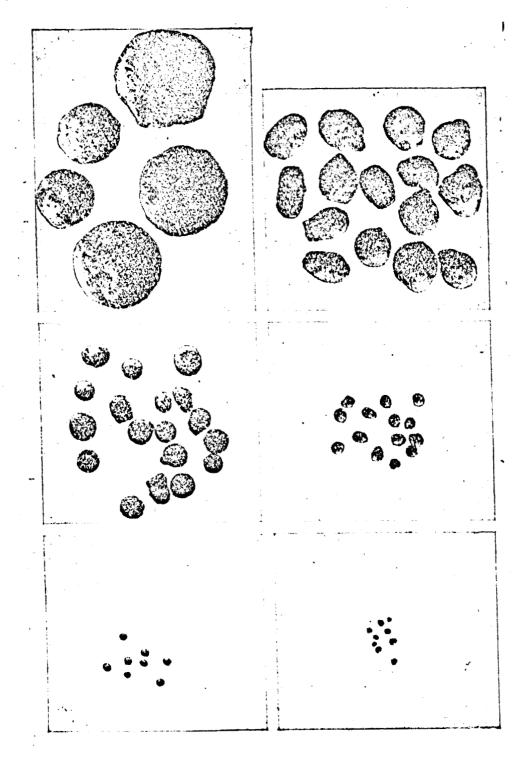


Fig.4 General View of Chondrules of the First Six Fractions and their Number per cm2 of the Saratov Chondrite (Side of a square, 1 cm)

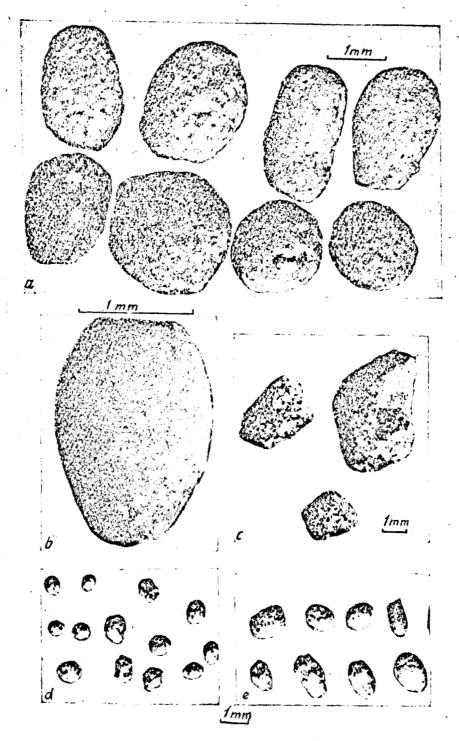


Fig.5 Shape of Chondrules

a - Spherical, ellipsoidal, pyriform, ovoid (bottom left); chondrules
from +1 mm fraction; b - Chondrule (cf. a - bottom left) under double
magnification; c - Chondrules of polyhedral shape from +2 mm fraction;
d - Chondrules from +0.5 mm fraction, in upper row on the right a fragment or shoot of a pyriform chondrule; e - Chondrules from +1 and
+0.5 mm fractions; upper right: smooth chondrule of elongated drop shape.

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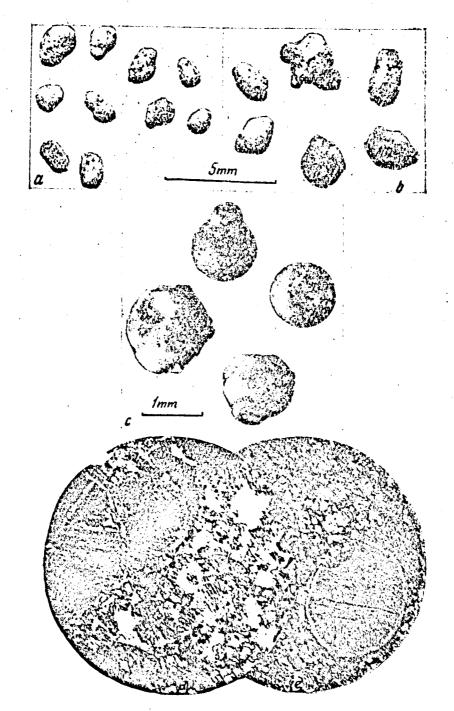


Fig.6 Altered Shape of Chondrules

a - Twinned chondrules from +0.5 mm fraction; b - Irregular shape of chondrules (the chondrules are swollen as a result of coalescence of several chondrules of simple shape) from +1 mm fraction; upper center, one chondrule of cylindrical shape; c - Chondrules (pyroxene) of spherical shape with holes (dents) and offshoots; d - Chondrule with outgrowth, viewed under microscope, both chondrules of pyroxene; d = 3 mm; Nikol'skoye chondrite, polarized transmitted light, without analyzer; e - Microscopic view of two combined chondrules of different structures; the chondrule with a hole, as always, is pyroxene; d = 3.5 mm; Savchenskoye chondrite, polarized transmitted light, without analyzer.

supplemented by the following observations:

- 1. The holes ("dents") are observed only among pyroxene chondrules, mainly those of eccentric-radiate-fibrous texture.
 - 2. Two types of conglomerates of chondrules are distinguished.
- a. Mutual indentation in the case of chondrules of different composition and structure. The acceptor in this case is always a pyroxene chondrule of eccentric-radiate-fibrous texture. Figure 6, e shows a photomicrograph of a highly instructive example of such a conglomerate of chondrules of the Alla Savchenskoye chondrite, unaltered by recrystallization. In such a combination, a chondrule or chondrules are easy to separate from the pyroxene chondrule, leaving regular holes on its surface (Fig.6, c, e etc.).
- b. Intergrowth of chondrules. In such cases, the chondrule, originally of simple shape, shows growths whose shape varies: from thin ragged to almost integral chondrules (Fig.6, a, b, part of chondrules in Fig.4, c and d). As seen in transparent sections under the polarizing microscope, the chondrule growths merely are pyroxene chondrules of eccentric-radiate texture (Fig.6, c and d). Pyroxene eccentric-radiate chondrules often also grow on another pyroxene eccentric-radiate chondrule; this is also observed in chondrules of different composition and structure. In all cases, a concave surface is observed on the chondrule which is the growing one. This means that the surface of one of the chondrules had already solidified or was highly viscid and served as a nucleus (or nuclei) of crystallization for the ambient liquid which obviously had not yet solidified at that time (cf. Fig.6, d etc.). It should be noted that pores of elongated shape in chondrules are always observed on their ends, while forms that are asymmetric relative to elongation (for example ovoid) occur at the broad ends (cf. Fig.1, b or c).

Cases of complete coalescence of chondrules, or absorption of smaller chondrules (obviously already hardened) by larger ones, are well known and were described as far back as Roze (Bibl.19). Such a combination of chondrules is best observed in transparent sections under the polarizing microscope; the literature contains many micrographs and descriptions [for example (Bibl.19 - 22) and others], but several of such coalescent and absorbed chondrules have been observed directly inside spallate chondrules.

3. Surface of the chondrules. In addition to the type of surface of the chondrules, which is usually defined as rough or smooth (Bibl.20 - 22, and others), the relief of the surface and its texture must be distinguished. The texture is visible (stands out) on the surface of the chondrule and reflects the structure of the aggregate making up the chondrule. The character of the chondrule surface, its relief and texture, just like its degree of smoothness, are interdependent and closely connected with the mineralogical composition and structure of the aggregate forming the chondrules.

According to its relief, the surface is defined either as smooth or unrelieved (in this case, it may be either rough or smooth; such relief is usually
characteristic of chondrules of eccentric-radiate and skeletal, or bar-like,
structure as well as of vitreous chondrules; cf. Fig.7, a etc.) or on the other
hand as a relief chondrule and in addition (usually) rough [such a relief is
characteristic of chondrules of microporphyritic and holocrystalline structure
(cf. the largest chondrule in Fig.7, a)].

According to texture, the following chondrule surfaces have been defined: banded and complex banded, spotty or microporphyritic, prismatic-granular ("bandaged chondrules"), fine-grained and with no texture at all, which may also be either smooth or rough.

The texture, observed on the surface of chondrules, reflects the internal structure of the chondrule, i.e., corresponds respectively to the eccentric-radiate-fibrous and in some cases to the barred structure of the chondrules, to the microporphyritic, prismatic-granular, holocrystalline, fine-grained, almost holocrystalline, and vitreous structures of the chondrules, respectively.

a. The striated or banded surface is highly characteristic and attracts special attention, permitting a differentiation of chondrules of a certain composition and texture from others. Such a surface is typical of chondrules 146 of widely varying size, shape, and color (cf. Fig.7, a etc.). Two forms of banded surfaces can be distinguished: ordinary surfaces on which the bands, distinctly visible under the binocular microscope, appear either in the form of a system (or systems) of parallel bands (the bands themselves) whence the name (Fig. 7, a, upper right etc.), or in the form of a system of radial bands (Fig.7, a, top and bottom), or else in the form of eccentrically arranged circles or ellipses (Fig. 7, a, third from bottom) with a point in common on the periphery of the chondrule. These pictures depend on the direction of viewing relative to the center from which the planes of growth of the silicates or the rays intersecting the surface of the chondrule diverge. This surface (which we will call banded) confirms the geometric pattern, presented by D.P.Grigor'yev (Bibl.23), of the crystallization of chondrules whose planes of growth diverge from one point lying on the surface of the chondrule. It should be added that these planes of growth generally have a radiate form, along eccentrically positioned rays or prisms of silicates, mainly of rhombic pyroxene, corresponding to a spherulitic crystallization with nonuniform feed (Bibl. 24).

In other cases, which are considerably less frequent in the Saratov chondrite. either concentric circles or a system of parallel striations are observed

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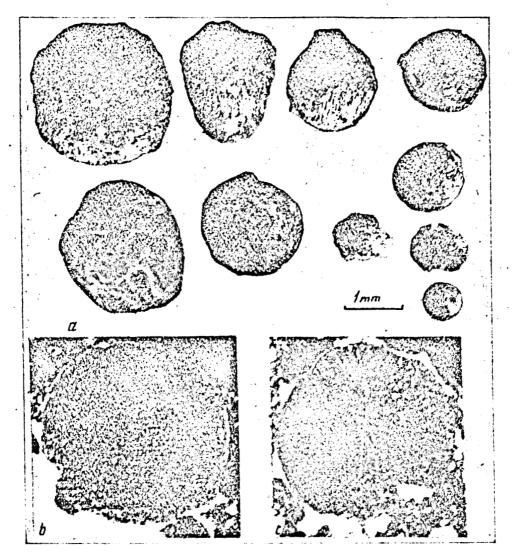


Fig.7 Surface of Chondrules, their Relief and Texture a - Surface of chondrules from various fractions; most of the chondrules have a banded surface of its own relief; visible are the systems of divergent bands (top right), parallel bands (small chondrules), two intersecting systems of bands corresponding to two different systems of planes of growth and pencils of prism of the complex-eccentric-radiate texture of the aggregates [chondrule on right; rough surface of chondrule with microporphyritic texture (largest one on the left) and uneven surface corresponding to prismatic-granular structure of chondrule ("bandaged chondrule") middle in second row]; b - Section of chondrule of eccentric-radiate texture perpendicular to planes of growth, made up of thin prisms with interstitial brown, almost opaque glass (black); view under microscope, diameter of chondrule 1.44 mm, Saratov meteorite, transmitted polarized light, without analyzer; corresponds to cross section of third banded chondrule (lower left, a) on plane parallel to plane of photograph; c - View of chondrule of complex-eccentric-radiate texture under microscope; corresponds to third case shown in a; various cross sections, transverse and longitudinal, appear for the prisms of pyroxene of various thickness and located in the planes of growth (both systems on the right) or with a bundle (dark region on left); diameter of chondrule 0.74 mm, Saratov meteorite, transmitted polarized light, without analyzer.

on the surface of the chondrules. Such cases obviously correspond to skeletal crystallization in which there is growth of parallel planes of a more or less isometric single crystal whose external shape is given by the volume and form of the liquid. This surface pattern obviously corresponds to chondrules of barred structure without a peripheral shell. Such a skeletal crystallization is far less frequent than the eccentric-radiate texture among the chondrules of the Saratov meteorites.

Surfaces with differently oriented intersecting systems of bundles of bands are observed. Obviously, they correspond to different bundles of planes of growth in chondrules of complex eccentric-radiate texture and, in the case of systems with parallel planes of growth independently of the cross section, to a complex barred structure. This pattern can be seen in Fig.7, a (second row to the right) and its corresponding form in a transparent section in Fig.7, c.

- b. Spotty or fine-grained surfaces. These are observed perhaps more often than any others among the chondrules of the Saratov meteorite. Usually such surfaces are rough. The spots on a surface of this type correspond to the microporphyritic segregations of silicates, outcropped on the surface of the chondrules and segregated among the inclusions of the fine-grained or glassy matrix (Fig.7, a, largest).
- c. Prismatic-granular surfaces, in chondrules made up of pyroxene prisms. The faces of the prism (sometimes with clearly distinguishable vertical striations) are arranged parallel to the surface of the chondrule, fitting on its rounded contours (cf. also Fig.10, c). In this case, the regular shape of the chondrule is somewhat disturbed, the surface becomes marked by relief, and the chondrule takes a form that appears bandaged (Fig.7, a, middle in second row).
 - d. Fine-grained uniform surfaces, with the finely crystalline structure

still distinguishable.

4. Surface holes on the chondrules. A characteristic and important detail of the appearance of the chondrule surface is the presence of rounded openings. As we were able to convince ourselves on spallation of the chondrules, these openings are the ends of channel-like cavities running into the interior of the chondrules (Fig.8). Such openings or orifices also occur widely in chondrules of other chondrites, and have been noted earlier in chondrules of the Nikol'skoye meteorite (Bibl.4). Such orifices or exits of cavities will be considered 47 below, together with a description of the porosity of chondrules.

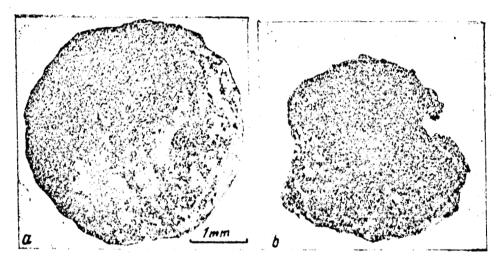


Fig.8 Chondrule with Orifice or Exit of a Channel to the Surface; Saratov Meteorite a - Form of orifice on the surface; b - Form of exit and channel in the plane of cleavage

Speaking of the surface of chondrules, it should be mentioned that, in addition to the fact that this surface often is covered by nickel-iron particles and, to a lesser degree, by troilite, there often are films of extremely fine granules of olivine (?), which are difficult to distinguish. Sometimes the surface appears as though sprinkled with a fine white - barely contrasting - powder.

- 5. Fracture of chondrules. The character of the fracture has been observed in both natural and artificial cleavage planes of chondrules. Its nature is determined by the internal structure of the aggregate composing the chondrule and by its mineralogical composition. The fracture of chondrules was noted long before microscopes were used in meteorite studies (Bibl.19, 21, and others). It may be said that a conchoidal fracture is typical for microporphyritic chondrules. The flat surfaces of spallation characterize chondrules of eccentricardiate and skeletal texture, corresponding to the planes of growth of the silicates. Natural cleavages of chondrules along such planes are frequent (cf. Fig.1, b). The number of naturally spallated chondrules is great (cf. Table 1), but some part of the chondrules were undoubtedly destroyed during fractionation of the specimen.
- 6. Color of the chondrules. The color of a clean surface of a chondrule varies. In some cases one can even speak of the transparency of chondrules to a certain depth. The prevalent colors of chondrules are white, gray, light gray, dark gray, almost black. White chondrules with greenish and irregular tints are not uncommon.

B. Structure of Chondrules and Texture of the Constituent Aggregate

1. Structure of chondrules. The cleavage planes of the chondrules clearly show that the constituent aggregate is either homogeneous or exhibits inhomogeneity, distributed by zones relative to the surface of the chondrule (Fig.9). This zonality is expressed either in the appearance of lighter peripheral fringes (Fig.9, a, second row left) of the fine eccentric-radiate texture observed in many chondrules, or in the appearance of a finer-grained sheath covering the nucleus of the chondrule, always of a different (often coarser-grained)

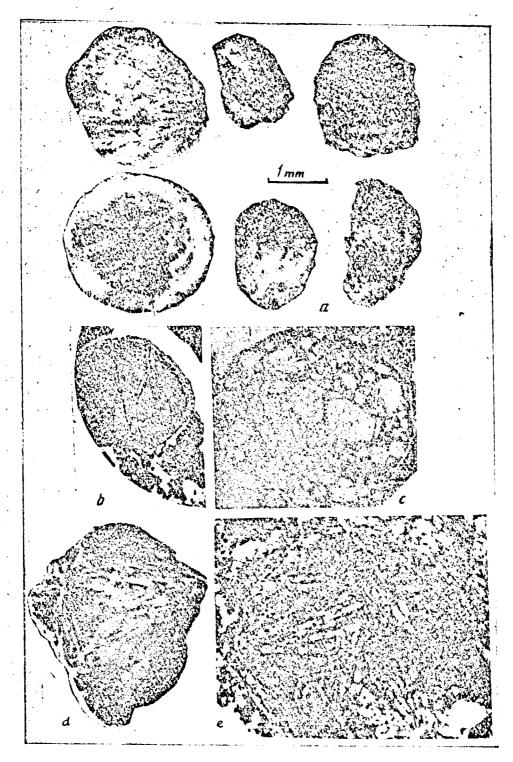


Fig.9 General Internal Structure of Chondrules and Cleavage Planes of Chondrules of the Saratov Meteorite a - Homogeneous structure of eccentric-radiate chondrule (upper left) and zonal structure of two types; compact chondrule with peripheral fringe (bottom left) and chondrules and parts of chondrules consisting of a shell and nucleus, separated by a loosely filled cavity; (cont'd)

b - View of chondrule with peripheral fringe under the microscope, chondrule diameter about 1.5 mm; c - Uneven surface of microporphyritic chondrule, possibly with torn shell; in this case, only the nucleus, chondrule diameter 0.84 mm, transparent section, transmitted polarized light, without analyzer; d - Pyroxene (bronzite) chondrule of eccentric-radiate texture with several crystallization nuclei, chondrule diameter about 2.3 mm; e - Microscopic view of chondrule of eccentric-radiate texture with four crystallization nuclei, chondrule diameter 2 mm; corresponds to the chondrule in Fig.d; Krasnyy Ugol chondrite, transmitted polarized light, without analyzer.

Zonality of this kind occurs in chondrules, mainly of microporphyritic texture. and holo- or hemicrystalline types. Often a zone consisting of a cavity, /49 loosely filled with mineral matter, is observed between the peripheral zone or shell and the nucleus of the chondrule (Fig.9, a, right). The shells are therefore easily separated from the more compact nucleus of the chondrules. Porous shells on chondrules have been noted by Čermak (Bibl.20). It could be thought that, in any case, a portion of such easily cleaved and brittle shells were formed from the silicate part of the matrix cementing the chondrules (cf. infra). This is not inconsistent with the rough surface of many chondrules, especially of microporphyritic type, and would be difficult to explain by theorizing that this was the original surface or a surface with flaws. It would be much more logical to assume that this constitutes the surface of nuclei of larger chondrules (Fig.9, c). However, it must not be forgotten that the shells on chondrules described repeatedly [for example, (Bibl.22, 9) etc.] might have formed later, during recrystallization of the chondrites, and then had become distinguishable from the nucleus. Such recrystallized peripheral zones, observed in a number of cases, point toward a primary zonal structure of the chondrules.

2. Texture of the constituent chondrule aggregate and druses. As shown by observations under the binocular microscope, porosity is a characteristic feature of chondrules. The porosity of the chondrules themselves, [except for

statements by Čermak (Bibl.20) on porous mantles on chondrules] has never been reported previously, as far as we know. Several authors (Bibl.25 and others) considered the absence of pores a characteristic feature of chondrules. Pores are present in many chondrules and, in some places, in great abundance. They are located inside the chondrules and often have openings toward the chondrule surface, as already discussed (cf. Fig.8). Two types of pores can be distinguished: rounded pores and druses whose shape is determined by the shape of the enclosing crystals.

1) Rounded pores (Fig.10, a, d, e), comparable with the pores of terrestrial lavas. These are observed in chondrules of microporphyritic structure. The same form of pores, gradually changing into druses, at times (or often) occupying the central portions of chondrules, are also encountered in the compact chondrules of eccentric-radiate texture.

Pore filling. In some cases, the surface of dark smooth chondrules of almost spherical shape appeared pierced (obviously as a result of the thinness of the wall), and the resultant cavity was filled with a brittle snowy white aggregate of extremely fine crystallites (Fig.10, b). According to the optical and other properties - refractive index Ng' = 1.633 + 0.002, very low birefringence (in many grains the mineral appeared isotropic), and ready solubility in dilute nitric acid - the mineral can be classified as apatite (?). An additional support for the theory of this being a phosphate is the presence of chemical phosphorus in the meteorite. P.N.Chirvinskiy (Bibl.9) called attention to the fact that this chemically detected phosphorus does not necessarily confirm the microscopic presence of apatite; he even proposed calculating the phosphorus as a phosphide possibly present in the nickel-iron. However, it is more likely that this phosphorus enters the apatite in brittle drusoid aggre-

gates of the cavities, which, of course, could not have remained in original form during preparation of the microscopic sections. In several chondrules, cleaved for this special purpose, druses were encountered which were often central with the same aggregates. Such cavities also contained drusoid aggregates of fine, discrete tabular crystals of sulfides, fractions of a millimeter

/50

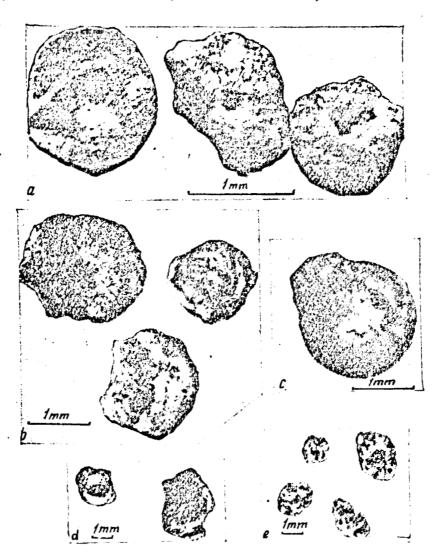


Fig.10 Porous Texture of Chondrules

a - Rounded pores in chondrules of the Saratov meteorite; b - Druse in
chondrule of Saratov meteorite, partially filled with a setiform aggregate
of a snowy white mineral apatite (?); c - Druses of miarolitic type in
cleaved chondrules of the Saratov meteorite; the lower chondrule shows a
concave pyroxene prism, parallel to the chondrule wall and fringing part of
the pore; d - Druses in chondrules of zonal structure of the Saratov meteorite; e - Rounded pores in chondrules of the Nikol'skoye meteorite.

in size.

2) A second type of pores has a form determined by the shape of the enclosing crystals, and occurs widely in prismatic-granular holocrystalline chondrules (Fig.10, c). This porosity is comparable with the miarolitic (drusy) porosity of holocrystalline eruptive rocks. Such druses are observed in prismatic-granular holocrystalline chondrules. They are also found in holocrystalline chondrules of uniform texture and in the central parts of chondrules of zonal texture. In such cases, the surrounding cavities of the aggregate are microdruses.

In some chondrules of holocrystalline structure, the interstices of the pyroxene prisms are studded with a fine-grained sulfide aggregate which, as one could imagine, had filled the previously existing miarolitic cavities.

Porosity is much more pronounced in the Nikol'skoye meteorite chondrules /51 which, on the average, are larger. The pores are more abundant and larger in size. Some chondrules even take the form of hollow bodies (Fig.10, e). A portion of the pores is filled, obviously by later druses of idiomorphic crystals of sulfides.

In chondrules of zonal structure, the zone between the nucleus and the surrounding shell is loosely filled with mineral matter (cf. supra) and may actually be considered a druse (Fig.9, a, upper left; Fig.10, d, right). Many fragments of chondrules were observed. These were obviously parts of shells, having the form of a sheath with a smooth concave inner surface (Fig.10, d, left) but there is also a large proportion of chondrules with hollow bodies:

C. Mineralogical Composition of the Chondrules

The principal components of the chondrules of the Saratov meteorite are

olivine, rhombic pyroxene (sometimes clinopyroxene), and glass. Admixtures in the chondrules are troilite, nickel-iron, and chromite (Bibl.26, 27). Only occasionally does one encounter chondrules in which nickel-iron or, even less often, troilite are the principal minerals.

The predominant minerals make up the chondrules separately or together (as described above). Glass is always present in varying quantities. Even in holocrystalline chondrules does it persist in the form of extremely small residues inside individual mineral crystallites, indicating their skeletal crystallization. Residual glass also is present in most of the mineral crystallites, giving them a characteristic appearance. The peculiarity of this structure demonstrates that even such mineral fragments belong to the typical minerals of chondrules.

In connection with the question of "organized elements", it should be noted that even individual fragments consist either of intergrowths of glass and minerals (fragments of chondrules), or fragments of minerals with traces of a skeletal structure recalling particles of biogenic origin, for which they might be mistaken at a cursory examination or at unfamiliarity of the observer with the structural peculiarities of chondrules and their minerals.

Earlier investigators (Bibl.9, 11) identified the orthosilicate of the Saratov chondrite as almost pure forsterite, and its pyroxene as bronzite and clinobronzite. Our own identification of the composition of the principal silicates and glass are based on their optical properties and are limited mainly to measurements of the refractive index of the olivines (Nm), of the rhombic pyroxenes (Ng), and of the glass.

We measured the refractive indices of the minerals and glass from chondrules of various compositions and structure. Some of the figures obtained and the corresponding compositions of the minerals and glasses are listed in Table 2.

TABLE 2

REFRACTIVE INDICES* AND CORRESPONDING COMPOSITION OF OLIVINE, PYROXENE, AND GLASS OF CHONDRULES OF THE SARATOV METEORITE

Mineral and Glass	Characteristics of Grains	NE		Mole % Faya- lite	Mole % Ferro- silite	Weight of SiO2 in Glass. %
Olivine	Skeletal crystal		1.700	20	ı	
Olivine	Microporphyritic segreg.		1.686	17-18		
Olivine	Small granule of almost holocrystalline chondrule		1,688	19		
Olivine	Grain from holocrystal- line chondrule			19		
Glass	Brown		1.549			54
Olivine	Microporphyritic segreg.		1.702	15		
G) ass	Light brown with ultra- microlitic pyroxene		1.570			
Olivine .	Single crystal (zonal)	1.718	1.702	25 15		51
Clinopyroxene Glass	Grains from one poly- mineral chondrule	1.674	1		7—8	47
Olivine	Single crystal	1.720		1		
Rhombic pyroxene	White; from a holocrystal line chondrule ("druse")	1.688			16	
Same	From a black eccentric- radiate chondrule	1.694	i		23	
Pyroxene Glass	From one eccentric- radiate chondrule	1.690	1.61	5	19	4647
Rhombic pyroxene	From the fringe of a zone chondrule	1.67	4		7-8	10-41
Glass	Same		1			48
Olivine	Nucleus of zonal chondrul	e 1.71	8 1.69	0 23		
Olivine	Crystals about 2 mm in size from a chondrule	1.72	0 1.68	32 20-	22	
G) ass	From the interstices of olivine grains					53
Rhombic pyroxene	e Radial bundles of white prisms, somewhat brownis owing to glassy inclusio	h ns 1.69	2 1.6	84 20		
G) ass	Fills spaces between py- roxene and olivine					57-5
Pyroxene	Chondrules with druses	1.6	92		20	
Pyroxene (bronzite)	Grain fragment from +0.14 mm fraction	1.6	92		20	1

^{*} The error of measurement is not less than 0.002 and not more than 0.004

These data show that the composition of the very same minerals in chondrules of different structure and microstructure fluctuate considerably: in the olivines, from 15 to 25% of the fayalite molecule (Bibl.28); in the pyroxenes, from 8 to 20% of the ferrosilite molecule (Bibl.29). The composition of the

glass fluctuates within limits corresponding to refractive indices of approximately 1.540 - 1.615. These values pertain to a silica content of 57 to 46% (Bibl.30), i.e., to the composition of the glasses of basic and neutral terrestrial layas.

At the same time, the composition of the minerals and glass remains constant within a group of petrographically identical chondrules. The variation in the composition of the minerals corresponds in general to the sequence of their variations in the crystallization of the petrographic types, represented in \(\frac{52}{52} \) the chondrules and corresponding to the course of crystallization in the system MgO-FeO-SiO₂. Thus, the most highly magnesian mineral is the olivine of microporphyritic chondrules; the most ferruginous is the pyroxene of the eccentricaliate chondrules, which solidifies last.

II. MORPHOLOGICAL FEATURES AND MINERALOGICAL COMPOSITION OF SILICATE PARTICLES OF CEMENTING MATRIX OF CHONDRULES, AND THEIR NATURE

The particles belonging to the cementing matter make up the larger part of the +0.1/4 mm, -0.1/4 mm, and smaller fractions. The +0.1/4 fraction, in turn, is separated into fractions by specific gravity, a magnetic fraction and electromagnetic fractions (cf. above, Fig.2).

In most cases, the fractions obtained were termed monomineral (arbi- /53 trarily) from the predominance of some mineral or another. The +0.14 fraction was examined under the binocular microscope before and after its separation; no substantial change or comminution of the material by comparison with the original was noted. Table 3 gives the general morphological and mineralogical characterization of the fraction particles, obtained from examination under the binocular microscope.

MORPHOLOGICAL AND MINERALOGICAL CHARACTERIZATION OF PARTICLES OF FRACTIONS (SPECIFIC GRAVITY, MAGNETIC, AND ELECTROMAGNETIC)
OBTAINED FROM THE FRACTION +0.14 mm, WEIGHING 6.73 gm

Specific Gravity of Fraction	Weight of Fraction, gm	Type of Fraction and Mineralogical Composition	Morphological Characterization of Fraction Particles			
> 3.33	1.33	Magnetic: nickel-iron (pre- dominant), troi- lite, silicates	Fragments of particles of nickel-iron, troilite and silicates, sparse chondrules, mainly of troilite and nickel-iron.			
> 3•33	0•23	Electromagnetic 1. Troilite (troilite predominant)	Particles of monomineral grain of troilite, fine-grained aggregate of troilite, fragments of concretions of troilite wit silicates; chondrules, glass.			
	0.21	2. Olivine (oli- vine predominant)	Fragments of olivine crystals (predominant), pyroxene, and their concretions, at times with glass and troilite; occasional chondrules.			
	0.27	3. Olivine and other minerals	Fragments of olivine (somewhat predominant), smaller numbers of pyroxene fragments and concretions of both silicates and troilites, chondrule fragments, and chondrules.			
	0.1/4	4. Mixture of olivine, other silicates, and troilite	Same as preceding fraction, fragments of olivine likewise somewhat predominant, but more troilite in the concretions.			
	1.78	5. Residue, mix- ture of silicates and troilite	Residues of silicates, growths of silicates, troilite glass, chondrule fragments, and chondrules.			
≈ 3 . 3	0.11	Electromagnetic: 1. Pyroxene (predominant)	Fragments of pyroxene (predominant), olivine, chondrule fragments (pyroxene), sparse chondrules.			

Specific Gravity of Fraction	Weight of Fraction, gm	Type of Fraction and Mineralogical Composition	Morphological Characterization of Fraction Particles		
	0.77	2. Pyroxene (other minerals may also pre- dominate)	Fragments of silicates (pyrox- ene predominates), chondrule fragments, chondrules.		
< 3.3	1.11	3. Electromag- netic mixture	Fragments of silicates, chondrules pierced by glass (predominant), few growths of silicates with troilite, glass and chondrules.		
	5•95	Total weight of fractions obtained, 5.95 gm; loss of material during fractionation, 0.78 gm, i.e., about 11.5%.			

A subsequent examination of a series of immersion preparations of the fractions under the polarizing microscope and a crystallo-optical investigation of individual particles showed the silicate particles of the cementing matrix to be fragments of chondrules, comprising either parts of chondrules or fragments of minerals and glass that had made up the chondrules. It is easy to establish whether or not minerals belong to the chondrules, from the characteristic structure of the aggregates (cf. Fig.l, c) corresponding to fragments of the chondrule structure, from the character of inclusions of glass and opaque inclusions in the mineral fragments, and from the refractive indices of the /54 minerals and glass which did not exceed the limits of the refractive indices of mineral and glass of the chondrules. Glass was observed in all fractions, usually in intergrowth with minerals; in the fraction smaller than -0.1/4 mm, individual glass fragments were also found. This substantiates the assumption that the silicate part of the cementing mass of the chondrules, in the spherical Saratov chondrite, consists exclusively of matter of disintegrated chondrules.

The same statement holds for the Nikol'skoye chondrite and other chon-

drites.

The difference between the composition of the total cementing matrix and that of the chondrules consists in the substantially larger quantity of nickeliron and troilite in the cement (about 1/14 of the volume of the cement) than in the chondrules, not counting the extremely rare kamacite or kamacite—troilite chondrules (Bibl.26, 27). One very large spherical kamacite chondrule weighing about 1 gm and about 9 mm in diameter was found in the specimen No.363 of the Saratov meteorite. It has a somewhat rough surface and consists of a single crystal of kamacite (with Neumann lines) in which round grains of olivines are included.

The particles of nickel-iron and troilite of the Saratov meteorite, like those of other chondrites, have been studied previously (Bibl.26, 30, 31). From the shape and structure of their nickel-iron particles it was assumed that they are fragments of a larger body (Bibl.30, 31) and that they have a pallasite structure (Bibl.27). No further observations have been made, and the question will not be discussed here.

III. COMPARISON OF THE CHEMICAL COMPOSITIONS OF CHONDRULES AND SILICATE FRACTION OF THE CEMENTING MATRIX OF THE CHONDRULES

The first comparison of the chemical composition of the chondrules and of the cementing matrix, in one and the same chondrite, was performed by Howard in 1803 (Bibl.32) for the Benares spherical chondrite. He found that the chemical composition of this chondrite was similar to that of its chondrules. The same results were given by the chemical analyses of Berzelius (Bibl.33), Nordenschild (Bibl.31), Gombel, Schwager (Bibl.35) of the Blansko, Hessle, and Wittness chondrites, respectively. However, Fredholm (Bibl.36), who repeated the analysis

for the Hessle chondrite, and Baumhauer (Bibl.37), who ran a chemical analysis of the Tjabe chondrite and its chondrules, were able to demonstrate that there are considerable divergences between the chemical compositions of these chondrites as a whole and that of their chondrules.

To supplement microscopic examinations, M.I.D'yakonova and V.Ya.Kharitonova, at the request of the present author, analyzed chondrules of the Saratov and Nikol'skoye meteorites and the Saratov chondrite as a whole (Bibl. 38, 39). The chemical composition of the integral Nikol'skoye meteorite had been given somewhat earlier by the same authors (Bibl. 40). The results of chemical analysis showed differences between the content of nickel-iron and troilite in the chondrules and in the chondrites as a whole, as well as a close resemblance in composition of the silicate portions of both chondrites and chondrules. The difference in the chemical composition of the silicate portion of the chondrules and chondrites as a whole relates mainly to the silica content. In one case. it was higher in the chondrite (Saratov) and in the other, in the chondrules (Nikol'skoye; cf. Table 4). This difference is readily explained by the nonuniform destruction of chondrules of different composition and their conversion into cement, and by the fact that the smallest chondrules, usually of a vitreous type, were not separated and were not analyzed in the sample from the chondrules but in the sample from the whole meteorite.

The chemical compositions (Table l_{+}) of the silicate portion of the chondrules and whole chondrites of Saratov (vectors C_{ch} and C_{wh}) and Nikol'skoye (vectors H_{ch} and H_{wh}) are represented in the form of a vector diagram (Fig.11, Table 5) according to the method of A.N.Zavaritskiy (Bibl. l_{+} 1). For comparison, we also plotted the chemical compositions of the silicate portion of an average chondrite (Bibl. l_{+} 2) (vector Ch), three varieties of peridetite

TABLE 4

CHEVICAL COMPOSITIONS OF CHONDRULES AND CHONDRITES

Lher- Wehr- Meime-zolite lite, chite Average Average (Bibl. 41, 6.91 6.03 31.82 5.99 0.27 0.09 1 3.43 9.53 0.26 22.88 45.07 0.64 7.48 1.14 3.10 43.95 0.10 4.82 2.20 6.34 0.19 36.81 3.57 0.63 0.21 1.08 Average Harts-burgite (Saxonite) 40.65 0.11 1.25 2.53 6.15 0.18 42.36 1.29 0.29 0.13 5.02 Silicate Portion of Average Chondrite according to Urey and Craig (Bibl. 42) 46.00 0.13 3.04 17.44 0.31 28.60 2.28 1.21 1.21 သ 8 Chondrite 39.56 0.18 1.56 85.05 8.00 1.21 0.21 6.18 15.03 0.24 24.49 1.87 1.20 0.17 0.37 Nikol'akoye Chondrite (Analyses by D'yakonova and Kharitonova (Bibl. 40) Silicate.
Portion
of Chondrite as
a whole, 46.19 0.22 1.86 17.78 0.29 29.34 2.23 1.45 0.20 0.44 100.00 Silicate Portion of Chon-drules, 49.90 0.23 4.51 13.32 0.39 27.47 2.51 1.19 0.17 0.31 100.001 Chon-drules 47.91 0.22 4.31 13.04 0.37 26.39 2.42 1.14 0.16 27 88 96.81 0.76 0.19 0.95 2.17 00 Saratov Chondrite as a Whole (according to Data of Chirvinskiy (Bibl. 9) 41.02 0.11 1.66 13.02 0.36 25.09 2.26 0.50 0.09 85.45 7.25 0.99 8.24 6.29 0.68 Chondri te Mhole 39.29 0.17 4.30 11.72 0.31 25.12 2.36 0.91 0.15 85.12 8.56 1.29 10.12 4.17 25 Saratov Chondrite (Analyses by D'yakonova and Kharitonova (Bibl. 38, 39) Silicate Portion of Chon-drite as a whole, 46.58 0.20 5.09 13.62 0.38 29.79 2.79 1.09 0.17 0.29 8 001 Silicate Portion of Chondrales, 42.18 0.19 3.64 13.35 0.42 29.98 2.59 1.19 0.16 o.3 100,00 Chon-drules 45.91 0.18 3.47 12.91 0.40 28.57 2.47 1.13 0.15 0.28 1.70 0.26 1.96 2.18 99.91 Total of silicate El ements SiO, TiO, Ai,O, MRO CiO Na,O KiO CiO, CiO, FeS ű Z portion Total Total

TABLE 5

NUMERICAL CHARACTERISTICS (FOR FIG.11)

Peremeters Legend on Fig. 11	a	r	ь	s	ľ	m'	e'	n
Cch	2.31	0.77	52.9	44.1	19.7	76,9	3.4	90.5
Cwh	2.22	1.66	52.92	43.2	20.4	77.5		0.0
Hch	2.45	1.23	49.87	46.45	21.3	76.2		86.6
Hwh	2.25	0.75	54.8	42.2	23.8	72.4		88.4
Ch	2.4	0.5	53.8	43.3	22.0	74.6		89.0
H	0.6	0.3	63.2	35.9	10.0	88.6	1.4	83.3
L	1.3	1.9	57.4	39.4	11.1	86.2	2.7	83.3
W	2.8	1.9	50.4	44.9	20.9	67.1	12.0	75.0
M	0.6	1.2	62.1	36.1	16	75	9	80

(vectors H, L, and W), and meimechite (Bibl.43) (vectors M) which are very close in mineralogical composition and in structure to the microporphyritic chondrules. It is obvious from the diagram that the chemical composition of the chondrules of the Nikol*skoye meteorite is particularly close to the chemical composition of wehrlite.

IV. SUMMARY OF THE RESULTS OF OBSERVATION

The data of these observations can be summarized as follows:

- 1. The silicate portion of the Saratov spherical chondrite consists mainly of chondrules and of fragments of disintegrated silicate chondrules.
- 2. The silicate portion of the cementing matrix of the chondrules consists either of particles in which the internal structure of the chondrules can still be distinguished, or of fragments of individual minerals and glass composing the chondrules.
 - 3. The chondrules exhibit individual peculiarities of structure.
- 4. A characteristic feature of chondrules is the porous texture of the constituent aggregate. We can distinguish a porosity similar to that of lavas

and a porosity similar to that of miarolitic (drusitic) holocrystalline rocks.

The cavities often have exit channels with an orifice on the chondrule surface.

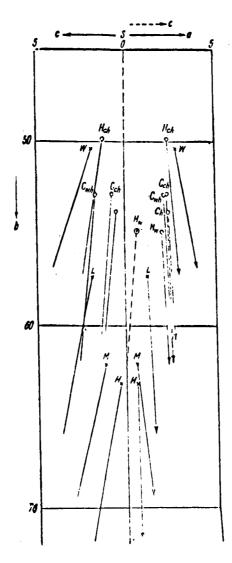


Fig.ll Vector Diagram of Chemical Compositions of Chondrules and Saratov and Nikol'skoye Chondrites, Silicate Portion of the Average Chondrite, and Varieties of Ultrabasic Rocks

5. It has been found that flaws in the configuration of the chondrules, having to do with an accretion or mutual contact of the chondrules and having the shape of regular holes, are encountered only on the surface of pyroxene chondrules and were formed there from previous indentations made by chondrules

- 6. The compositions of the mineral and glass constituents of a chondrite vary within definite limits, which are constant for petrographically identical chondrules.
- 7. Cavities within the chondrules are filled with mineral admixtures [apatite (?), sulfides] in the form of drusy aggregates.

Conclusions

- 1. The chondrules must have crystallized, as independent bodies, from a liquid of given composition and volume.
 - 2. A characteristic feature of chondrules is their porosity.
- 3. In the chondrites, the following should be differentiated: a) porosity of the chondrules themselves, produced by gases dissolved in the mother liquor, and b) porosity of the chondrite as a whole, produced by the conditions during the accumulative phase and the conditions of accumulation of the aggregate of which the chondrite consists.
- 4. The porosity of the chondrules can be compared with the porosity of lavas or with the porosity of holocrystalline rocks, while the porosity of a chondrite as a whole is comparable with the porosity of detrital rocks of the type of volcanic tuffs or sintered tuff-ignimbrites. In fact, the figure of 18 vol.%, characterizing the porosity of the Saratov chondrite (Bibl.14), is within the limits of the corresponding values for ignimbrites (Bibl.44).
 - 5. Judging from the holes formed on the surface of pyroxene chondrules and

from the growing pyroxene chondrules on chondrules of different composition, the pyroxene chondrules must have solidified later than the others.

- 6. The size distribution of chondrules can only be approximately calculated; this parameter does not determine the primary distribution of the chondrules in the chondrite, since some of the chondrules are destroyed and converted into cement. The size distribution is most accurately determined in chondrites with cement consisting only of nickel-iron and troilite.
- 7. The silicate portion of spherical chondrites unaltered by recrystallization, of the type of the Saratov chondrite, consists only of chondrules; their detritus, together with shards of the minerals and glass, constitute the silicate portion of the cementing mass of the chondrules.
- 8. The chondrules and chondrites are simultaneous or almost contemperaneous formations.
- 9. The formation of the impurity minerals (sulfides and others) or at least of a portion of these, must have taken place after solidification of the chondrules. This could have promoted sintering of the entire constituent aggregate of the chondrite.
- 10. Structural data of the chondrules indicate beyond doubt that they were formed from drops of liquid, but the question as to how these drops were formed, whether by melting of an atomized solid matter or of a potentially liquid matter, or else by condensation of a gas, will require supplementary extensive petrographic investigations and experimental verification.

The results of the first experiments performed in this direction (Bibl.45, 46) do not contradict the possible formation of chondrules by the melting of a finely divided solid.

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